

On the mechanism of low-mass compact object formation

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**Abstract**

*We suggest that low-mass compact objects (hadron stars, quark stars) with  $M < 1 M_{\odot}$  can appear only due to fragmentation of rapidly rotating proto-neutron stars. Such low-mass stars receive large kicks due to an explosion of a lighter companion in a pair of fragments, or due to dynamical ejection of one of the lighter components in the case when three bodies are formed.*

*As far as low-mass compact objects are expected to be slowly cooling in all popular models of thermal evolution possible candidates are expected to be found among hot high velocity sources.*

In many models of thermal evolution of compact objects (neutron stars – NS, hybrid stars – HyS, strange stars, – SS) low-massive sources with  $0.8 M_{\odot} < M < 1 M_{\odot}$ <sup>1</sup> remain hot for a relatively long time (about few million years)<sup>2</sup>. During all that time they remain hotter than more massive stars (Blaschke et al. 2004 and references therein). In that sense they are promising candidates to be observed as *coolers*, and their detection is of great interest for physics of dense matter (Carriere et al. 2003). However, in most of models of NS formation (Woosley et al. 2002; Fryer, Kalogera 2001, Timmes et al. 1996) no objects with  $M < 1 - 1.2 M_{\odot}$  are formed. It is like that just because masses of stellar cores are always heavier than  $1.2 M_{\odot}$  even for the solar metallicity (and heavier for lower metallicity, see Woosley et al. 2002 figs. 14 and 15).

In our opinion the only way to form a low-mass object from a (relatively) high-mass core is fragmentation (see however a discussion in Xu 2004, where the author discuss formation of low-mass SSs from white dwarfs via accretion induced collapse).

Fragmentation of a rapidly rotating protoNS due to dynamical instabilities as part of a two-stage supernova (SN) explosion mechanism was suggested by Imshennik (1992) (see also Imshennik, Nadezhin 1992).<sup>3</sup> This mechanism can explain several particular features of SN explosions (for example delay in neutrino signal from SN1987A, see a recent discussion of this topic in Imshennik, Ryazhskaja 2004). In this scenario a compact object inevitably obtains a high kick velocity. Recently the mechanism (in application to kick) was studied in some details by Colpi and Wasserman (2002). Because of high temperature the exploding (lighter) companion can be significantly more massive than the minimum mass for cold stars (i.e.  $\sim 0.1 M_{\odot}$ ) up to  $\sim 0.7 M_{\odot}$  (see Colpi, Wasserman 2002). In that case from the initial object of, say,  $1.2 - 1.3$  solar masses due to fragmentation and explosion of the lighter part, we can finally have a high-velocity NS with the mass about 0.8-1 solar masses or lower if the mass of the initial object was smaller.

Even lower masses can appear if due to fragmentation three bodies are formed. In that case the lightest or an intermediate mass fragment can be dynamically ejected from the system (again with significant velocity about thousands km s<sup>-1</sup>). Such ejected compact objects can have masses about 0.2–0.5 solar masses. In the remaining pair the lighter one can start to accrete onto the second companion because of the orbit shrinking due to gravitational waves emission, and after reaching the minimum mass ( $\sim 0.1 M_{\odot}$ ) it explodes. So, the remaining compact object would also have relatively low mass ( $\sim 1 M_{\odot}$ ) and high velocity.

Objects formed after fragmentation have particular predictable properties: high spatial velocity, high surface temperature, velocity vector nearly perpendicular to spin axis (as far as kick is always obtained in the orbital plane which coincides with the equator of the initial protoNS).

Due to high kicks low-mass compact objects are not expected to appear in binaries (at least they should be rarely found in binary systems). To find a low-mass compact object one has to search for a hot young high velocity NS.

The best place to look for young hot compact objects are supernova remnants (SNRs). Several so-called central compact objects (CCOs) are known (see reviews in Becker, Aschenbach 2002 and in Kaplan et al. 2004). For example Cas A, Puppis A and 1E 1207.4-5209. The last one was suggested to be a low-mass quark star candidate by Xu (2004). Cas A is known to be a mysterious source with very small estimated emitting area and relatively high temperature (0.7 keV), see Chakrabarty et al. (2001), Pavlov et al. (2000). Puppis A is known to be a very hot source for its age (0.4 keV at 3.7 kyr, see Kaplan et al. 2004). However in the case of low-mass NSs the extremely high kick velocity can spoil this approach of searching. If kick velocity is up to 10,000 km s<sup>-1</sup> (as it is estimated in Colpi, Wasserman 2002 for their case 2, i.e. for lighter component with the mass  $\sim 0.3 M_{\odot}$ ) then a NS travels up to 1 kpc in just 100,000 years! In that case they quickly leave the Galaxy, and of course there is little hope to find them inside SNRs.

There is a possibility, that a rapidly rotating protoNS can just loose part of its mass in the form of an outflow in the equatorial plane. In that case two spiral arms appear, no second (or third) component is formed, and kick can be relatively small, but the fraction of lost mass is very small: about 4% (Houser et al. 1994), and so the final mass cannot be much lower than the initial one.

It is reasonable to expect that mass and kick velocity are anti-correlated, as far as a higher mass of the remaining object corresponds to the lighter exploded component, which means to a wider orbit, and to lower orbital velocity of the remaining more massive component. Also higher kicks lead to smaller fall-back (Colpi, Wasserman 2002).

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<sup>1</sup>Here and below speaking about compact objects we mean the gravitational mass.

<sup>2</sup>Objects with even lower mass,  $\sim 0.5 M_{\odot}$ , also are relatively hot (Blaschke et al. 2004).

<sup>3</sup>Note that the English-language versions of these papers are available via NASA ADS.

To reach fragmentation conditions (the dynamical instability) it is necessary that progenitor core is rapidly rotating. Rotation of isolated progenitors and its influence on properties of newborn NSs was studied in several papers (see, for example, Heger et al. 2003 and references there in). To obtain a rapidly rotating compact object it is necessary to avoid spin-down influence of the magnetic field, so probably compact objects born after fragmentation should be low magnetized. It means that low-mass neutron stars are not expected to be normal radio pulsars. Because of the same reason they are not expected to show any kind of magnetar activity.

It is interesting to investigate the possibility of a fossil disk formation around a compact object which experienced fragmentation. Very low masses of discs (about  $0.1 M_{\odot}$  and lower, Menou et al. 2001) are necessary in models which explain SGs and AXPs properties, and such small amounts of mass are definitely available after fragmentation.

Evolution of progenitors in close binaries was studied by several groups (see Langer et al. 2003, Podsiadlowski et al. 2003 and references there in). There are arguments both *pro et contra* formation of rapidly rotating protoNSs in close binaries. Iben and Tutukov (1996) discussed the possibility that fast rotation of a compact object can be reached only in close binaries due to tidal corotation or due to accretion. Langer et al. (2003) showed, that the primary (more massive) star in the binary can hardly produce a rapidly rotating remnant as far as such stars loose angular momentum due to mass loss. On the other hand these authors suggested, that the secondary (which accretes matter and so angular momentum) can be a progenitor of a short period compact object. So, progenitors of low-mass NSs can be secondary components of close binaries. It gives an opportunity to estimate the formation rate of such objects.

There is a possibility that a low-mass compact object can appear to be not a normal (hadron) NS, but a quark star (a hybrid one or a bare strange). The phase transition can appear long time after a NS formation or during the very first episodes of NS's life (see for example Olinto 1987). One can think about a rather exotic possibility of phase transition of newborn fragments into quark phase due to compression (increase of the central density) observed in numerical experiments by Mathews and Wilson (2000). Initial results of these authors (see Mathews, Wilson 1997 and references to earlier papers there in) were found to be incorrect (Flanagan 1999), but re-calculated models were not under serious criticism and they still showed a moderate level compression during NS-NS coalescence (see also Gourgoulhon et al. 2001, Oeshlin et al. 2002), but the degree of compression is close to numerical accuracy of calculations. In addition to these uncertainties in the case of protoNSs fragmentation high temperatures and fast rotation of new-formed fragments can exclude high densities which are necessary for the phase transition. Anyway, to form a low-mass quark star it is necessary at first to form a low-mass NSs and here, in our opinion, fragmentation is the only mechanism, but the role of compression is unclear (and probably negligible). One alternative to compression can be a delayed phase transition in a low-mass NS due to formation of a critical-size drop of strange matter (Berezhiani et al. 2003), but the "waiting time" (mean-life time of a metastable configuration) for a low-mass object is estimated to be very long (Bombaci et al. 2004). Another alternative is a strangelet passage through a star (see however a discussion in Balberg 2004). Such transition to quark matter can also produce additional energy release. These objects are particularly interesting as far as low-massive HySs and SSs in contrast with low-mass hadron NSs can have relatively small radii, and this feature can help in fitting observational data (see for example Xu 2004 for a discussion).<sup>4</sup>

We have to note, that the mechanism of SN explosion suggested by Imshennik (1992) has its internal problems. If the fragmentation in the process of NS formation never happens in Nature, then, in our opinion, it is very improbable, that low-mass compact objects can exist. Discovery of a high velocity low-mass NS, HyS or SS will be a strong argument in favour of the Imshennik mechanism.

To conclude: fragmentation of a protoNS can be a unique mechanism of the formation of low-mass compact objects, which are expected to have several peculiar characteristics that can help to distinguish them among possible candidates.

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<sup>4</sup>Phase transitions due to compression can be discussed also in the standard scenario of binary NS coalescence.

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